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Simulation of a walking robot-exoskeleton movement on a movable base

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The paper studies the problem of movement of a two-legged walking machine on a movable base, presents a mathematical model that allows to obtain the kinematic parameters of the movement of the executive units of the device under study. The paper presents a method for planning the trajectory of exoskeleton links, its algorithmic and software implementation. The paper presents the results of numerical experiments, analyzes them, and makes conclusions based on the research results.

Keywords: walking robot, mathematical simulation, kinematic analysis, trajectory planning

1. Introduction

Exoskeletal devices are widely used for rehabilitation of patients with disorders of the musculoskeletal system [1-9]. The maximum effect is achieved when the patient and the exoskeleton form an integrated human-machine system (HMS), the effectiveness of which is determined by the degree of consistency (synchronicity) of the elements of this system, including the human and active exoskeleton. To meet this requirement, the system contains a human-machine interface (HMI), which is a technical means that provides interaction between the patient and the exoskeleton. This system, consisting of the patient, the exoskeleton, and HMI was named bio-electromechanical system (BEMS).

The BEMS structure consists of an exoskeleton, a human-machine interface, a patient, and a support surface. At an early stage of rehabilitation, the patient occupies a passive position, and the movements of the lower limbs are performed using an exoskeleton along program-defined trajectories in accordance with the rehabilitation exercises performed, for example, the patient's walking on a path. At later stages, a combined mode of BEMS operation is possible, in which at certain times the patient takes an active position and the exoskeleton implements the movements set by the patient, and at another time the operator switches to a passive mode, and the exoskeleton performs the movements set by the program.

Various control strategies are implemented in these modes. In the first case, we can talk about a tracking control system, and in the second one – about a combination of tracking and copying control strategies.

As the review of information sources shows, most scientific works consider walking on a fixed base, which in most cases reflects the real conditions of the use of walking machines, but in the case of creating a rehabilitation complex, the task of studying walking on a mobile base, synchronizing the movement of the walking device and the moving surface is relevant [10-11]. Within the framework of this work, mathematical models of the movement of BEMS executive units and algorithms of the motion control system that provides collaborative functioning of the human exoskeleton and the mobile support surface are developed.

2. Mathematical model and formulation of the simulation problem

The paper deals with the lower limbs' exoskeleton during the walk implementation along the moving belt of a treadmill (Fig. 1). The upper part of the exoskeleton 1 is attached to a fixed base – the frame. The femoral links 2 (left leg) and 4 (right leg) by means of active joints that contain electric drives creating moments, that can have an assisting effect on the patient, are attached to the body. To control the relative position of the links, the active hinges are equipped with angle sensors and torque sensing systems. In a similar way, the femoral links are connected to the lower leg links 3 (left leg) and 5 (right leg).

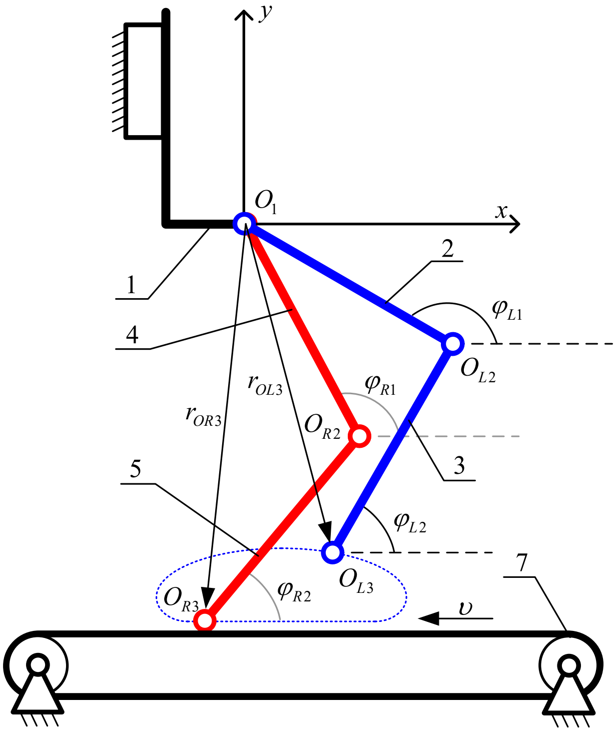

Figure 1. Design diagram of the device in the process

The task of the system that controls drives of the hip and knee joints of the device is to realize this relative motion of links, at which points O_{L3} and O_{R3} move along the desired trajectory, implementing a walking motion of the exoskeleton. An important feature of the desired trajectory is to ensure that there is no slippage or impact at the moment of contact with the surface, which is provided by the choice of appropriate boundary conditions. In this work there is a number of assumptions: the trajectory of the foot attachment point is symmetrical with respect to the vertical axis, the movable surface is parallel to the horizon, the size and shape of the feet are neglected, considering that the contact of the robot's links with the surface occurs through the points O_{L3} and O_{R3}.

For mathematical description of the kinematics of motion, there is a system of equations:

$$\begin{aligned} x_{OL2} &= x_O + l_1\cos(\varphi_{L1}) & x_{OL3} &= x_O + l_1\cos(\varphi_{L1}) + l_2\cos(\varphi_{L2}) \\ y_{OL2} &= y_O + l_1\sin(\varphi_{L1})\ ; & y_{OL3} &= y_O + l_1\sin(\varphi_{L1}) + l_2\sin(\varphi_{L2})\ , \\ x_{OR2} &= x_O + l_1\cos(\varphi_{R1}) & x_{OR3} &= x_O + l_1\cos(\varphi_{R1}) + l_2\cos(\varphi_{R2}) \\ y_{OR2} &= y_O + l_1\sin(\varphi_{R1}) & y_{OR3} &= y_O + l_1\sin(\varphi_{R1}) + l_2\sin(\varphi_{R2}) \end{aligned} \tag{1}$$

where l_1 and l_2 – long links, respectively: thighs and shins, x_O, y_O – coordinates of the femoral joint in the inertial reference system, $\varphi_{Li}, \varphi_{Ri}$ – absolute rotation angles of the left and right leg links.
The links' rotation angles can be determined in various ways, in the framework of this work, they are defined as follows:

$$\varphi_{L1} = \begin{cases} arctng\left(\frac{y_{OL3}}{x_{OL3}}\right) + \arccos\left(\frac{l_1^2 - l_2^2 + \left(x_{OL3}^2 + y_{OL3}^2\right)}{2l_1\sqrt{x_{OL3}^2 + y_{OL3}^2}}\right) \text{ if } \left(x_{OL3} > 0\right) \\ arctng\left(\frac{y_{OL3}}{x_{OL3}}\right) + \arccos\left(\frac{l_1^2 - l_2^2 + \left(x_{OL3}^2 + y_{OL3}^2\right)}{2l_1\sqrt{x_{OL3}^2 + y_{OL3}^2}}\right) - \pi \text{ if } \left(x_{OL3} \le 0\right) \end{cases}, \tag{2}$$

$$\varphi_{L2} = \varphi_{L1} + \left(\pi + \arccos\left(\frac{l_1^2 + l_2^2 - \left(x_{OL3}^2 + y_{OL3}^2\right)}{2l_1 l_2}\right)\right). \tag{3}$$

Using equations (2) and (3), it is possible to determine the absolute rotation angles of links when a point O_{L3} moves in the lower quadrants of the coordinate plane $(y_{OR3} < 0)$. The angles $\varphi_{R1}, \varphi_{R2}$ for the second leg of a walking machine can be obtained in a similar way.

3. Trajectory planning

The trajectories of the points O_{L3} O_{R3} are determined by the parameters of the mechanism, type of gait and step parameters. Let us introduce a coefficient that determines the shape of the trajectory of the points $k_\upsilon = \upsilon_f / \upsilon_b$, where υ_f is the speed along the linear part of the trajectory (movement together with the support), υ_b – is the maximum foot speed, for the symmetrical walking, it is the upper intersection point of the trajectory with the ordinate axis.
Using the coefficient, we can obtain a vector of gait parameters, $\bar{\mathbf{s}} = (s, h_s, H_s, k_\upsilon, T_s)^T$ in which s – is the step length, h_s - the height of the leg when walking, H_s - the distance from the hip joint to the treadmill running, T_s - the duration of one step. Note that the parameters s and T_s determine the walking speed and can be calculated based on the speed of the moving base.

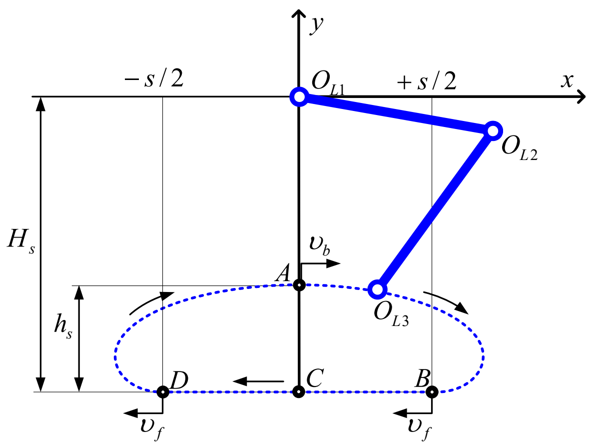

Figure 2. Planning the trajectory of moving links of a walking machine

Since the trajectory is symmetrical, it is convenient to use a piecewise polynomial function, splitting it into 3 fragments: AB, BD, DA.
In order to provide the continuity of the trajectory setting functions, as well as the lack of collision of the links on the surface, the conditions must be met at each point. Next, an example

related to the function for left leg is presented performed (for the right leg the function is going to be similar):

$$\text{At point A: } \begin{cases} x_{OL3} = 0; \\ y_{OL3} = -(H_s - h_s); \\ \dot{x}_{OL3} = \upsilon_b; \\ \dot{y}_{OL3} = 0. \end{cases} \tag{4}$$

$$\text{At point B: } \begin{cases} x_{OL3} = s/2; \\ y_{OL3} = -H_s; \\ \dot{x}_{OL3} = -\upsilon_f; \\ \dot{y}_{OL3} = 0. \end{cases} \tag{5}$$

$$\text{At point D: } \begin{cases} x_{OL3} = -s/2; \\ y_{OL3} = -H_s; \\ \dot{x}_{OL3} = -\upsilon_f; \\ \dot{y}_{OL3} = 0. \end{cases} \tag{6}$$

Polynomial functions for changing coordinates, can be represented as follows:

$$\bar{q}(t_0, t_{last}, q_0, q_{last}, \dot{q}_0, \dot{q}_{last}, t) = \left(\sum_{i=0}^{3} k_i t^i \right)^T, \tag{7}$$

where coefficients k_i are determined by:

$$\begin{bmatrix} k_0 \\ k_1 \\ k_2 \\ k_3 \end{bmatrix} = \begin{bmatrix} 1 & t_0 & t_0^2 & t_0^3 \\ 1 & t_{last} & t_{last}^2 & t_{last}^3 \\ 0 & 1 & 2t_0 & 3t_0^2 \\ 0 & 1 & 2t_{last} & 3t_{last}^2 \end{bmatrix} \cdot \begin{bmatrix} q_0 \\ q_{last} \\ \dot{q}_0 \\ \dot{q}_{last} \end{bmatrix}, \tag{8}$$

Where, in our case t_0 – initial time of the trajectory fragment, t_{last} – final time, $q_0, \dot{q}_0$ – initial value of the coordinate and its derivative, $q_{last}, \dot{q}_{last}$ – final value of the coordinate and its derivative corresponding to the trajectory fragment.

In order to record the simultaneous trajectories of the both legs of the device, an additional point has been introduced into the trajectory. This point corresponds to the *A* point in the trajectory for the other leg. Trajectory recalculating in a loop can be implemented as a function mod (*a, b*). This function returns the remainder of dividing *a* by *b*. Thus, the use of the equations for coordinates $O_{L3}\ O_{R3}$ becomes possible by setting the length of the step T_s and dividing it by 8 equal intervals $[t_A, t_B),\ [t_B, t_C),\ [t_C, t_D),\ [t_D, t_A) \in t$, where $t = \text{mod}(Time, T_s)$, $Time$ – current time value.

$$\begin{cases} x_{OL3} = q(t_A, t_B, 0, (s/2), \upsilon_b, -\upsilon_f, t); \\ y_{OL3} = q(t_A, t_B, -(H_s - h_s), -H_s, 0, 0, t); \\ x_{OR3} = -t\upsilon; \\ y_{OR3} = -H_s; \end{cases} \text{if } (t_A \le t < t_B) \tag{6}$$

$$\begin{cases} x_{OL3} = -t\upsilon_f + s; \\ y_{OL3} = -H_s; \\ x_{OR3} = q(t_B, t_C, (-s/2), 0, -\upsilon_f, \upsilon_b, t); \\ y_{OR3} = q(t_B, t_C, -H_s, -(H_s - h_s), 0, 0, t); \end{cases} \text{if } (t_B \le t < t_C) \tag{7}$$

$$\begin{cases} x_{OL3} = -t \cdot \upsilon + s; \\ y_{OL3} = -H_s; \\ x_{OR3} = q\left(t_C, t_D,\ 0, (s/2), \upsilon_b, -\upsilon_f, t\right); \\ y_{OR3} = q\left(t_C, t_D, -\left(H_s - h_s\right), -H_s, 0, 0, t\right); \end{cases} \quad \text{if } \left(t_C \le t < t_D\right) \tag{8}$$

$$\begin{cases} x_{OL3} = q\left(t_A, t_D, (-s/2), 0, -\upsilon_f, \upsilon_b, t\right); \\ y_{OL3} = q\left(t_A, t_D, -H_s, -\left(H_s - h_s\right), 0, 0, t\right); \\ x_{OR3} = -t\upsilon_f + 2s; \\ y_{OR3} = -H_s; \end{cases} \quad \text{if } \left(t_D \le t < t_A\right) \tag{9}$$

By setting the step parameter values, it becomes possible to obtain different trajectories of the O_{L3} point movement.

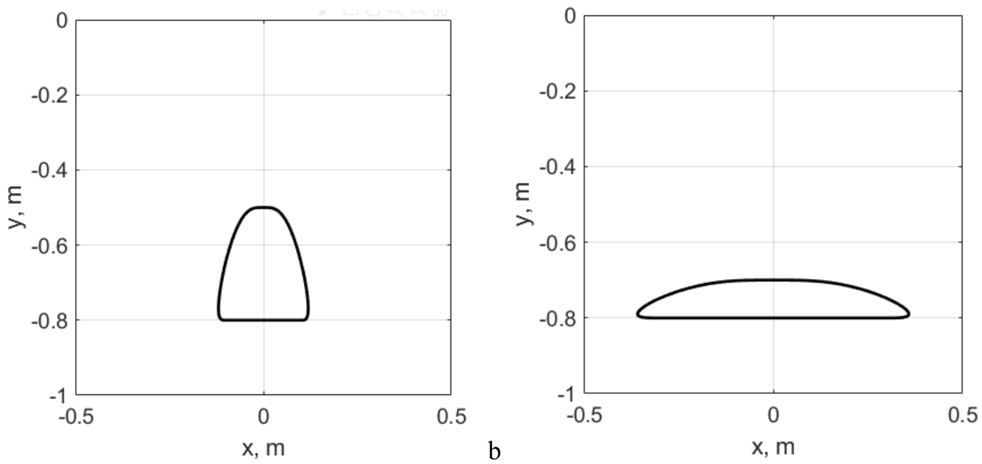

Figure 3. Trajectories defined by equations (6)-(9) for the step parameters:
a - $\bar{\mathbf{s}} = (0.2, 0.3, 0.7, 0.5, 4)^T$, b - $\bar{\mathbf{s}} = (0.6, 0.1, 0.8, 0.25, 4)^T$

As shown in the graphics, the developed trajectory planning algorithm allows obtaining a continuous trajectory for multiple step parameters. When the coefficient k_υ decreases, the trajectory becomes elongated, due to the synchronization requirements imposed to the links movement, which are composed of a movable base (collision is not stipulated).

Using the trajectory shape coefficient k_υ results possible to obtain the required law of movement of links. This law is necessary to establish the parameters of the mechanotherapy of a specific patient, which simplifies the configuration and preparation of equipment.

4. Numerical simulation of the movement of the acting links of a two-legged walking machine-exoskeleton on a movable base

Mathematical modeling of the device movement at walking on a movable base stage has been performed. The length of the links of the device (0.5 m), as well as the step parameters $\bar{\mathbf{s}} = (0.5, 0.2, 0.8, 0.5, 1)^T$ has been specified.

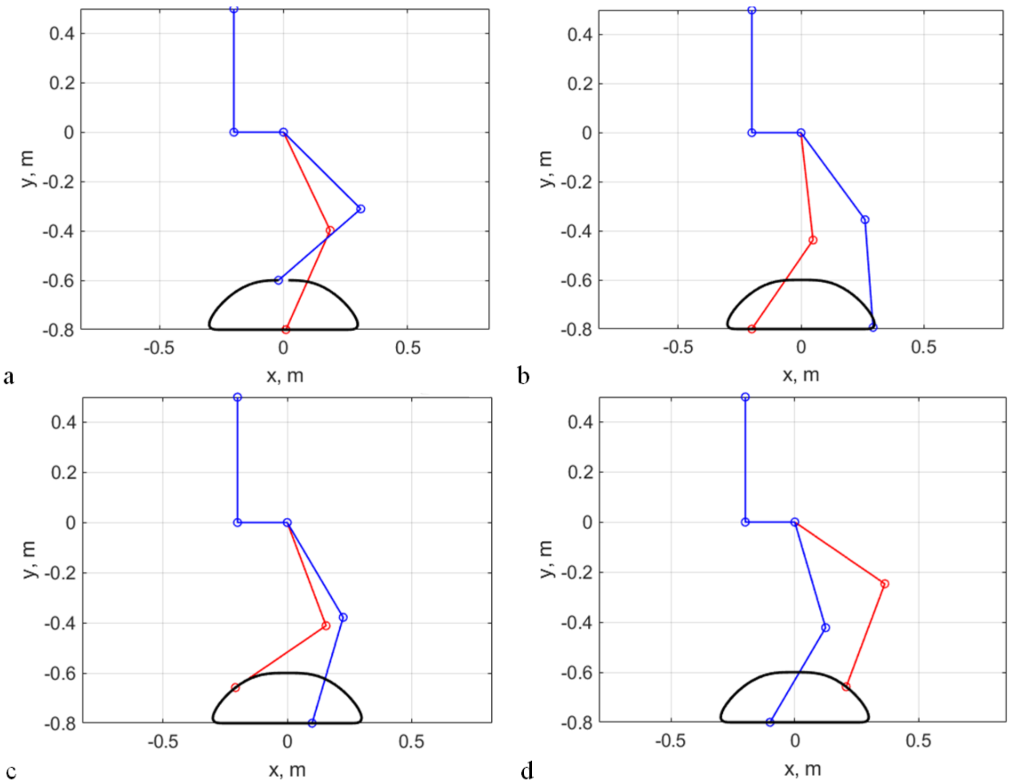

Figure 4. Walking simulation results: a – at 0s, b – at 0.2s, c – at 0.4s , d – at 0.6s.

In Fig.5 a space-time diagram for the coordinates O_{L3} and O_{R3} is presented.

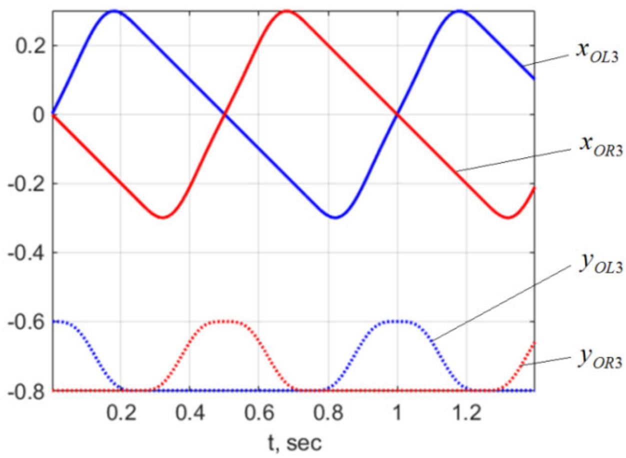

Figure 5. Law of change of the coordinates O_{L3} и O_{R3} at trajectory performing

During the modeling process, absolute and relative angles related to the movement of the links were also obtained when the symmetrical trajectory of movement of the links of the acting mechanism of the two-legged walking machine on a horizontal movable base is performed.

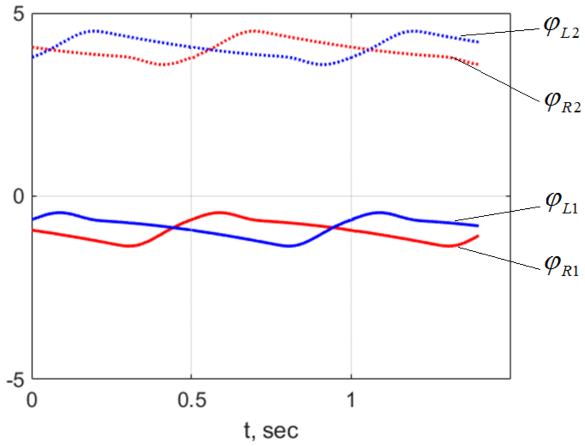

Figure 6. Laws of change of the absolute angles of rotation of the device links at trajectory performing

During the development process of an automatic control system is convenient to use space-time diagrams (Fig.7) of the change of relative angles (represented in degrees).

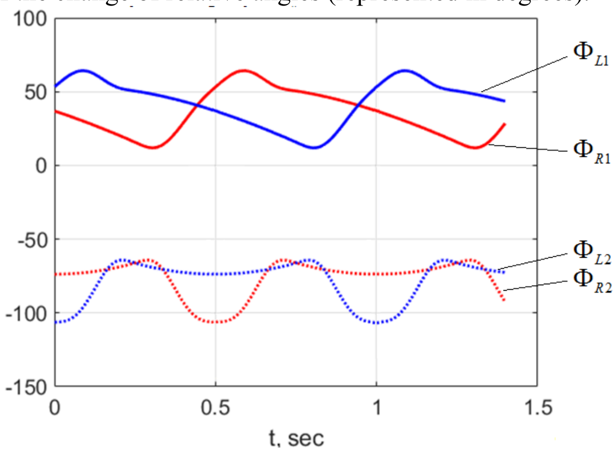

Figure 7. Laws of change of the relative rotation angles of device links at a given trajectory performing

5. Conclusions

A mathematical model of the movement of a two-legged walking mechanism on a movable base of a treadmill has been carried out. A method for studying this mechanism has been proposed. Also, trajectory planning algorithms have been developed, as well as the equations for solving the inverse kinematics problem for the mechanism links have been written. In order to set the shape of the trajectory, a coefficient k_υ is proposed. This coefficient represents the relationship between the speed values of movement of the legs on the surface and above the surface. Also, this coefficient in conjunction with other step parameters, such as length, height and duration, allows getting the required movement of the links of the walking mechanism, which are necessary for conducting a mechanotherapy treatment. The presented method is approved by mathematical modeling, which demonstrates the applicability and appropriate operation of the developed algorithms for trajectory planning for robot-exoskeleton devices.

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